INVITED

RESEARCH PROFILE: PRIME POWER FOR HIGH-ENERGY SPACE SYSTEMS

A. K. Hyder, Jr., Auburn University, AL 36849
P. J. Turchi, R&D Associates, Alexandria, VA 22314
H. L. Pugh, AFOSR, Bolling AFB, DC 20332

Summary

By the year 2000, an increasingly larger portion of our national defense, and perhaps, civilian enterprise will depend on space-based systems. Extrapolation of present trends indicates that prime-power sources approaching the megawatt level and beyond will be needed. These power levels must be achieved at significantly higher values of specific power (W/kg) and energy (W-hr/kg) than are presently available in order to satisfy these space-based needs. While steady progress has been made and new concepts have provided the potential for further improvements, substantial gains over the next two decades will require investment in basic research examining fundamental processes and phenomena in power conversion, material behavior, surface interactions, etc. Pulsed electrical power levels in excess of 100 MW may also be required by various future space-based military systems. Such pulsed levels may be repeated and sustained long enough to require significant heat and mass transfer resembling steady power-system operation. The particular problems of a specific device presently under development are less important than the creation of tools, data, and techniques on which the technology rest. A broad-based, fundamental research program is necessary that will support development efforts in the next two decades. Although there are many system-specific research topics that demand attention, three areas of basic research were identified at the Special Conference on Prime Power for High-Energy Space Systems as generic to all power systems: characterization and design of materials, fluid interactions, and plasma interactions. A discussion of specific research opportunities within these areas is presented.

Introduction

A recent study of potential requirements for prime power sources for defense space systems indicates that steady electric power levels approaching one megawatt will be needed by the end of this century.[1] Pulsed electrical-power levels in excess of 100 MW will probably also be required by various future space-based weapons systems. Such pulsed levels may well be repeated and sustained long enough to require significant heat and mass transfer resembling steady power operation.

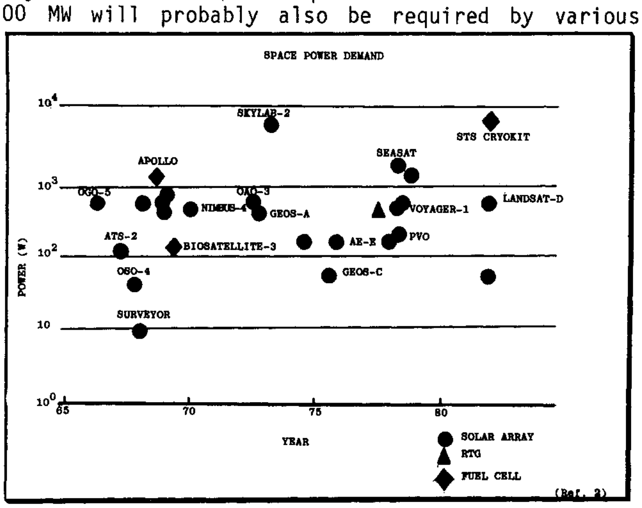

Figure 1. Historical summary of NASA space power demands.

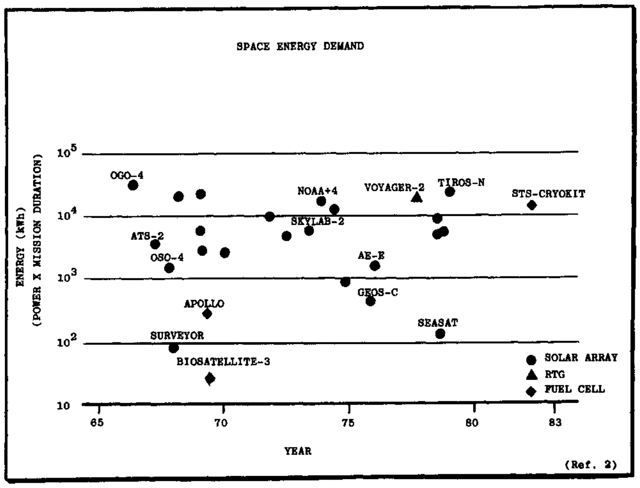

Figure 2. Historical summary of NASA space energy (power x mission duration) demands.

The historical trends for both space power and space energy (power x mission duration) have shown only mild upward slope,[2] as shown in Figures 1 and 2. These trends were doubtless constrained by the available space-power technology; indeed, until megawatt space-power sources are in hand, it is unlikely that missions that require such sources either will be authorized or receive widespread support. An increase in energy demand of over three orders of magnitude is, however, predicted over the next two decades for NASA programs,[2] rising to demands in excess of 10^8 kWh by the beginning of the next century (Figure 3).

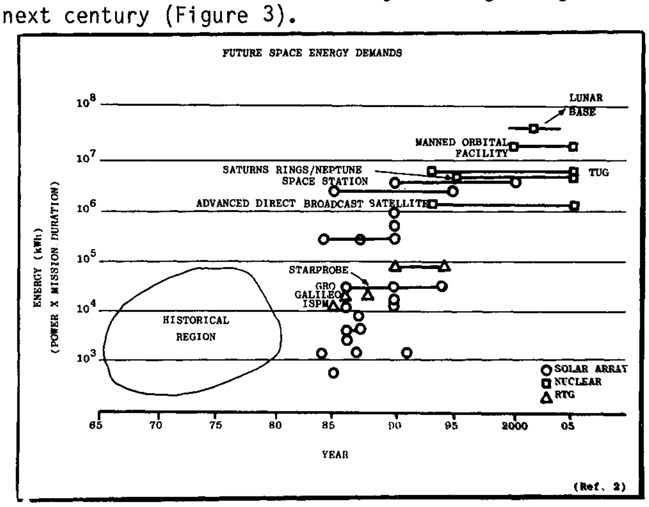

Figure 3. Projections of future space energy requirements for NASA projects.

Military missions in space will demand even more dramatic power technology improvement. Representative military uses are summarized in Figure 4. While many of these needs may well be satisfied with current technology, the more demanding ones, those requiring megawatt power sources, will not. As the enabling research underpinning these power technolo-

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1983	**N/A**	**-**

4. TITLE AND SUBTITLE
Research Profile: Prime Power For High-Energy Space Systems

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Auburn University, AL 36849

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**7**	

gies is reported, the ability to field and the willingness to propose systems demanding megawatt levels of power will increase. These high energy systems for military missions will also be subject to a host of constraints imposed by weight limitation, reliability, survivability and vernerability, life-cycle costs, etc. which will be considered before ultimate deployment.

POWER RANGE	1 - 25 kW (e)		25 - 500 kW (e)	MW (e)
ENERGY SOURCE	SOLAR	RADIOISOTOPE	SP-100, CHEMICAL	ADVANCED REACTORS
CONVERSION SYSTEM	PHOTO-VOLTAIC	THERMOELECTRIC RANKINE BRAYTON	THERMOELECTRIC THERMOPHOTOVOL	RANKINE, BRAYTON MHD, THERMIONIC
COMMUNICATIONS		●		
NAVIGATION GRID		●	●	
WEATHER		●	●	
TREATY MONITORING		●	●	
HARDENED C^3			●	
SPACE-BASED RADAR			●	
SPACE-BASED IR TRACKING			●	
BLUE-GREEN LASER			●	
ELECTRONIC JAMMERS			●	
HIGH-ALTITUDE LARGE OPTICS			●	
CHEMICAL LASERS -WEAPONS		●		
-COMMUNICATIONS		●		
DEEP-SPACE COMMAND CENTER			●	
ELECTRICAL PROPULSION			●	●
CISLUNAR SUPPLY VECHILE				●
SPACE PLANE				●
FREE-ELECTRON LASER				●
PARTICLE-BEAM WEAPONS			●	●
WEAPONS STATIONKEEPING		●		
OTHER ADVANCED WEAPONS				●
LUNAR BASE				●

(Ref. 11)

Figure 4. Power requirements for possible defense applications.

To reconcile the present lack of specific need with what is a certain future requirement for high levels of prime power, a broad-based, fundamental research program is necessary to support space power in the remaining two decades of this century. In such a research program, the particular problems of a specific device presently under development are less important than the creation of the tools, the data base, and the techniques upon which future technologies may rest. Idealy then, specific problems of the present should be generalized to identify and solve fundamental questions generic to all of space prime power. The understanding obtained in this research effort would then provide the basis for developing prime power systems which will enable the performance of future high-power missions.

An effort to do just this was made at the Special Conference on Prime Power for High-Energy Space Systems. It was convened with the objective of identifying that limited set of research topics, presumably not system-specific, which must be addressed now if power technology is to make the large leap which will be demanded of it. By identifying

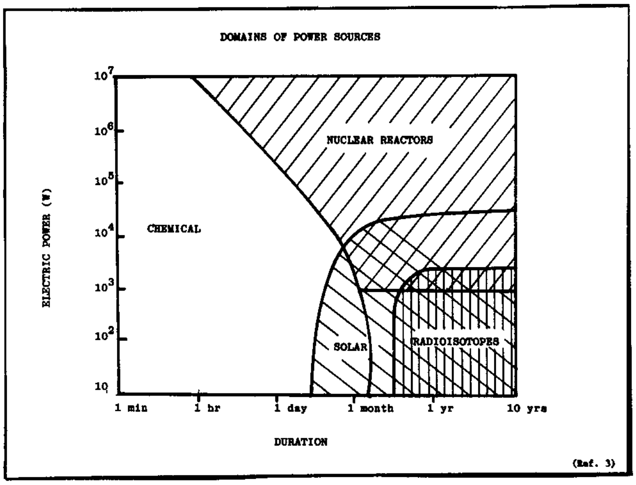

Figure 5. Domains of possible space power sources.

the fundamental physical limitations, understanding the controlling perameters, and then devising techniques by which these perameters can be adjusted to obtain higher performance, new levels of capabilities can be achieved, guiding the development of new devices, components, and systems.

Overview of Space Prime Power

Many techniques exist for obtaining electrical power in space. The relative merits of a particular system and the optimum combination of components and processes depend primarily on mission requirements. Such requirements may exclusively restrict options otherwise available to the system. The trade offs between power level and duration, shown in Figure 5, provides one example.[3]

It is useful to divide prime-power systems functionally into three parts: 1) energy generation; 2) conversion of source energy into electricity; and 3) rejection of thermal energy generated by inefficiencies in the generator and/or converter. The first functional part may not actually be contained in the spacecraft. For example, the sun or a laser beam could supply photon energy. Also, the energy source may be replenishable. The distinction between energy sources and energy storage (for pulsed-power or load-levelling) is somewhat arbitrary, but can be made in terms of physical and chemical processes. If the processes are the same as for a source that would be launched from the earth, then it is reasonable to treat any device, even if energized in space, as an energy source (e.g., batteries). If the device would not be launched in an energized state (e.g., high-speed, rotating flywheel), then it is more useful to consider it part of the power conditioning system, or in some instances, power conversion.

For each of the three functional parts, there are reasonably distinct technical categories. In

TECHNIQUES \ FUNCTIONS	ENERGY GENERATION	CONVERSION TO ELECTRICITY	HEAT REJECTION
	RADIANT Solar Laser Microwave	PHOTOELECTRIC Photovoltaic Laser inverter μwave antenna	RADIANT Conventional Liquid
	NUCLEAR Isotope Reactor Fusion	THERMAL Dynamic cycle MHD Thermoelectric Thermionic	EJECTION Open-cycle
	CHEMICAL Combustion Reaction	CHEMICAL Battery Fuel-cell Nuclear emission	STORAGE Molten salts

the energy generation area, nuclear and chemical processes are the fundamental sources; it is useful, however, to treat radiant source technology (solar, laser, microwave) as a major category also. In the area of energy conversion into electricity, three main categories exist: 1) photoelectric - photon energy converted directly to electricity, typically by direct interactions of photons and electrons; 2) thermal - heat converted to electricity by direct means (Seebeck effect, thermionic diode) or indirect means, involving transformation of heat into mechanical energy and then into electricity (MHD, Brayton, Rankine, Sterling, etc); and 3) chemical - reaction energy converted to electricity (battery, fuel-cell, beta-decay). Rejection of heat from the prime-power

system also has three main categories: radiation, storage, and mass ejection. The last two categories can be utilized in missions that require short intervals of high primepower levels; radiation is the only choice for steadystate power processing. Storage is also used benefically in some systems as a load-leveller. A diagram summarizing the functional and technical areas of space prime power is given in Table I.

Survey of Power Technology and Research Needs

The elements and relationships between parts of the power system are given in Figure 6.[4]

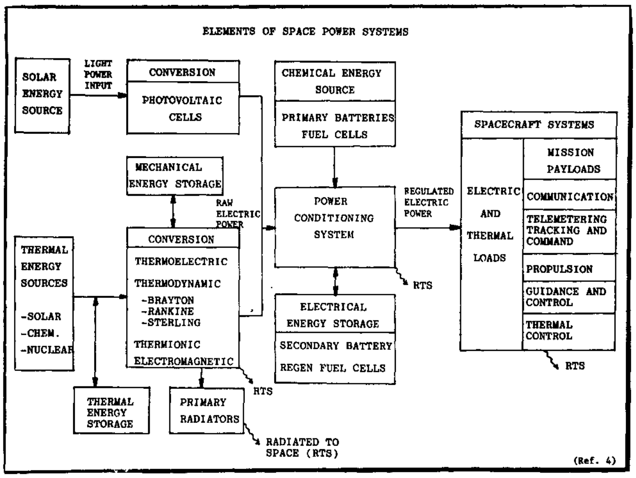

Figure 6. Relationships among various space power systems.

Radiant Systems

Prime-power systems based on radiant energy exist in two different forms. Some systems utilize photons in proper energy ranges to convert radiant energy into electricity by direct interaction of photons with electrons, (photoelectric effect, microwave-, laser-receivers, etc.). Other systems absorb photons over a broad range of energies in a manner that converts radiant energy into heat (scattering, reabsorbing, downshifting photon and particle energies in free and bound states). Heat is then converted into electricity by thermal methods, including thermoelectric, thermionic, and various dynamic cycles, (Brayton, Rankin, MHD, etc.) The two different forms of radiant energy system have quite distinct research problems.

For radiant-thermal systems, the concerns are essentially the same as for other thermal concepts. Basic research is needed on materials and material interfaces at high temperatures. As an example, consider the data on fatigue life of solar cell interconnecting systems shown in Figure 7. In this case, thermal cycling rather than high temperature loading needs to be addressed.[2]

Direct radiant-electric systems involve research topics that range from design and fabrication of multi-layer (tandem) photocells that more efficiently utilize the solar spectrum, to understanding the interactions of electromagnetic radiation with plasmas (solid or gaseous) in the context of electrical power generation. The former topic will probably include fundamental research questions on the characterization and modification of matter and will be closely related to other problem areas, such as thermoelectrics. Research on interactions with plasma might involve the utilization of transmitted laser radiation to excite plasmons, and could provide

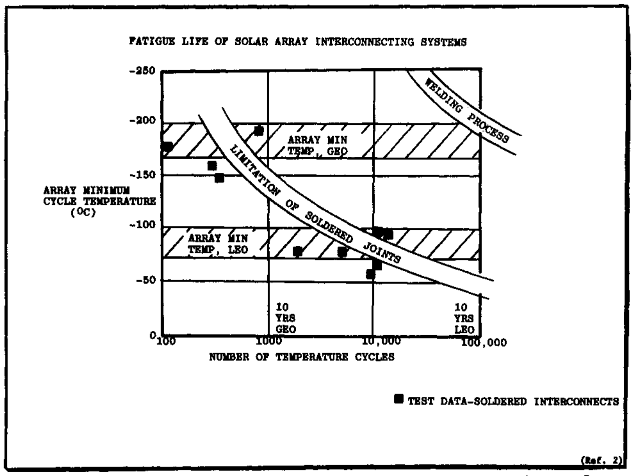

Figure 7. Limitations of soldered joints in solar array systems.

needed understanding of the coupling of randomly-phased radiation to plasma electrons.

An additional critical technology area for radiant systems based on solar power is the need for large structures to accumulate the required high levels of power. At 1 kw/m^2 incident power flux and 10% conversion efficiency, collection areas in excess of 10^4 m^2 would be needed for megawatt electrical power levels. The interactions of space-plasma and fields with such structural areas provide additional research problems that will occur also for large heat-rejection radiators, and possible defense payloads such as antenna arrays.

Chemical Sources

The use of chemical energy to create electricity is a well-established technology, typically found in a variety of batteries. In most terrestrial applications, battery systems appear relatively passive and the principal thrusts for development have been higher energy density, higher current capacity, lower cost, etc. Defense system applications place additional constraints, largely due to environment and limited access (e.g., underwater, in space). The basic ruggedness and reliability of battery systems are sufficiently attractive to maintain interest in extending battery performance into regimes for which other (more complex) techniques might otherwise be selected.

Fuel-cells have been developed relatively rapidly in support of space missions and can also be considered well-established technology. As with batteries, there is considerable impetus to extend capabilities to higher levels. Higher pressure operation appears to provide significant improvement. Also in common with batteries, the development of reversible (rechargeable) systems is particularly interesting. For missions in which very high power levels are needed intermittently for short durations, the use of fuel-cell reactants, such as hydrogen and oxygen, in combustion-driven MHD generators could provide a total system capability that would favor H2/O2 fuel-cells for modest, steady power requirements. Other reactants are, of course, possible and are under investigation.

Two directions for battery and fuel-cell development can be pursued. Since the basic technology is already well in hand, performance can be improved by testing devices and correcting failure modes. In some instances, performance limitations may be due to mechanical stresses as in higher pressure fuel-cell operation or system design may constrain the choice

of reactants to fuels needed by other power modes (e.g., H2/O2). Gradual evolution to higher performance should be possible, even empirically. In parallel with such evolution, fundamental studies of the interface chemistry and other interactions between electrodes and electrolytes may assist in selection of candidate reactants, catalysts and structural materials. Many aspects of these studies could prove useful to other parts of the prime-power system, such as surface reactions in heat loops.

MHD/Chemical Systems

MHD technology is capable of providing reliable high power for short times. One advantage enjoyed by MHD is the near instantaneous startup as seen in Figure 8. The operation times of such systems are limited by thermal loading and fuel supply. Uncooled heat sink systems can operate for times of the order of 100-150 seconds.[5]

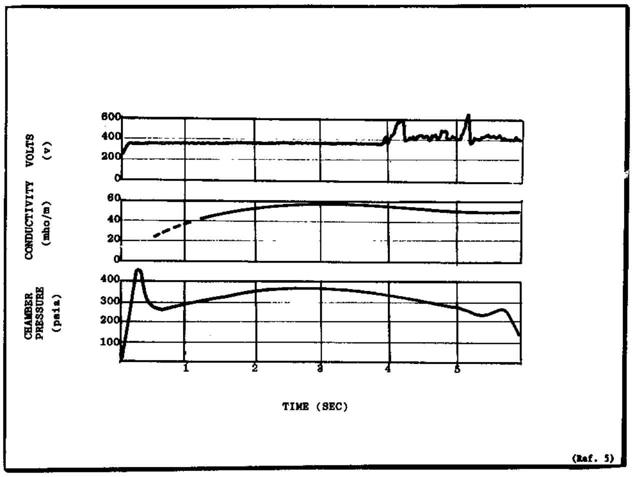

Figure 8. Startup of solid-grain MHD power source.

The technology of magnetohydrodynamic (MHD) power systems is associated with chemical systems because combustion is often used to provide the necessary high speed, electrically conducting flow. Apart from this association, MHD power systems do not utilize chemical reactions to generate electricity. There are however, critical chemical processes involved in MHD generators.

Basically, MHD power generation requires that a high-speed flow crossing a strong magnetic field possess sufficient electrical conductivity to allow significant currents to flow (magnetic Reynolds numbers unity). Such currents interact with the local magnetic fields to produce an electromagnetic body force that acts against the high-speed flow, converting kinetic energy into electrical energy. For gaseous or plasma flow, the electrical conductivity depends critically on the temperature and, sometimes, density of of the flow. The conductivity is, therefore, significantly affected by both the initial flow conditions (as provided, perhaps, by chemical combustion) and chemical processes (e.g., ionization/recombination) in the current-carrying flow. In the temperature regime that is typical of MHD power systems (0.1 - 1 eV), the conductivity and current density distributions can interact nonlinearly, providing significant variations from optimum performance characteristics (e.g., spokes).

All of the technology is based on an empirical appreciation of the physical phenomena. Little basic understanding of the boundary layer between the hot plasma and cold electrodes is available, and there is lacking an understanding of physical chemistry affecting surface interactions, conductivity, recombination, combustion chemistry, etc.

The interaction of the conducting flow with solid boundaries (electrodes and insulators) can be a critical area limiting MHD generator performance and lifetime. The basic physical processes of heat transfer, particle bombardment, and radiation interact closely with chemical processes of ionization, recombination, excitation, and are sensitive to such parameters as cross sections, species concentration, etc., at and near the solid boundaries. Nonuniform attachment of the discharge to electrodes, the degradation of insulators by particles and "triple-point" interations (where the discharge, electrodes, and insulator meet) are just a few of the basic problem areas. Many of these problems are shared by advanced propulsion systems (e.g., plasma thrusters), so common research interests exist. Some research interests would include development of experimental and theoretical techniques and a data base on electrode and insulator materials in a high energy discharge environment.

There are MHD generator concepts and systems that do not involve high-current gas-discharges, namely, liquid-metal/aerosol systems. In such generators, the conducting flow consists not of a gas, but a liquidmetal "seeded" with gas bubbles. Expansion of these bubbles provides the working mechanism by which heat energy (in the gas and liquid) is converted into flow kinetic energy. The liquid metal allows a high conductivity path for electrical currents between the generator electrodes. Interaction of these currents with magnetic fields again provides the electromagnetic forces that oppose the fluid flow and convert kinetic energy into electric energy.

Two areas of research in liquid metal/aerosol MHD generators are interactions of the hot liquid-metal flow with solid boundaries, and the mechanics of two-phase, multi-component thermodynamic flows. Both these areas occur in other parts of prime-power systems, such as liquidmetal thermodynamic cycles, heat pipes, and liquid-film or -droplet radiator systems. Common research questions can, therefore, be expected.

Nuclear Sources

Nuclear sources for electric power generation are well-established in terrestrial applications at very high power levels (>Mw) and in spacebased systems at levels presently adequate for many significant missions (~10 kw). The space-based systems in the past or present U.S. inventory include the

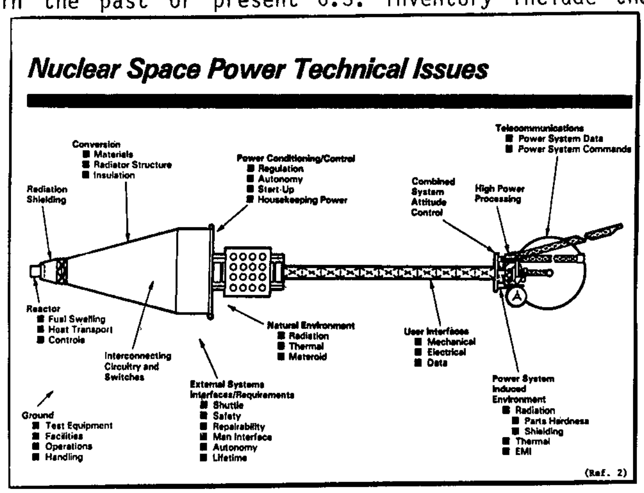

Figure 9. Nuclear space power technical issues.

radioisotope sources radiothermal generators, or RTG's, and dynamic-cycle approaches. The high-power systems are commercial-utility reactors and, at one time, also included systems applicable for use in space (NERVA, et al). Recently, interest has been generated in development of a space power-reactor at the 100 kW level, the SP-100. Also, concepts such as the rotating-fluidized-bed reactor have attracted attention.

With the substantial technology base developed over the past four decades, many of the tools, techniques, and data exist to develop high power space-nuclear systems. Problems, such as those addressed in Figure 9, do remain, however.[2] The principal problem is operating lifetime. This problem is specific to nuclear systems in terms of reaction induced damage and swelling, but common to all thermal power systems for space in terms of creep, loss of fatigue strength, integrity, etc. at the high temperatures required for rejection of waste heat.[6] The general problem area of material behavior at high temperatures, especially under conditions of mechanical stress and corrosion, is critical for basic consideration.

Within the context of the SPAR design, El-Genk and Woodall[3] suggest additional areas for research emphasis that go beyond a specific system: failure modes of incore heat pipes-rupture by fuel swelling, impurity accumulation in the wick, wall embrittlement through chemical reactions with fission products, stress corrosion cracking due to absorption of fission products; sublimation of UO_2 fuels; heat pipes modeling and bonding studies; innovative heat disposal schemes; and thermoelectric theory and materials. Thermoelectric conversion technology status is summarized in Figure 10.[7,8] Good thermoelectric materials exhibit a high Seebeck coefficient (α), a low electrical resistance (ρ), and a high thermal resistance (k) which combine to the figure of merit shown. Improvements in both the material efficiency and the high temperature stability are needed.

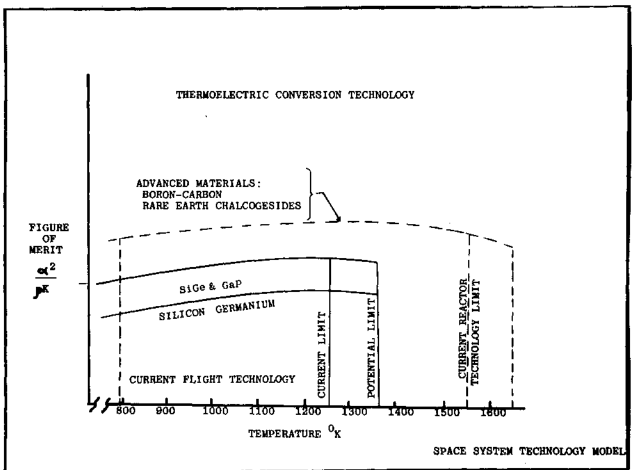

Figure 10. Temporatory and effiency limitations of thermoelectrics.

Power Conversion

The research area in nuclear sources that is common to all systems based on thermal energy is the behavior of materials at elevated temperature. Such research would apply within a nuclear source, to thermoelectric and thermionic converters, to Brayton, Rankine, and other thermodynamic cycles, MHD generators, and finally to various stages of the heat rejection system. In the area of power conversion, in particular, there are two types of high-temperature materials questions: experimental data on solid and liquids above 2000 °K; and physical understanding of phenomena at high temperature, including the means to specify and achieve desired materials behavior. The former question reflects the difficulties associated with performing experiments in the higher temperature regimes that may be suggested by system optimization studies. The latter type of question includes such concerns as the scaling of the figure of merit-temperature product in thermoelectrics, and approaches to preventing corrosion of high-temperature, alkali-metal flow loops. A common research area is the interaction of high-temperature materials at interfaces. The physical/chemical basis for perparation of materials, bonds, coatings, etc., can be examined in such research.

Thermionics

Power generation using thermionics becomes attractive when high temperature sources are available to heat electrons directly out of a cathode. An anode at lower temperature can then be placed close enough to the cathode to collect significant electrical currents. Electron emission from metals is a strongly-increasing function of temperature so the anode can function even at a relataively high temperature (~1000 °K) which allows substantial reduction of the radiator area needed for heat rejection. Combined with high temperature sources (e.g., nuclear), thermionic conversion thus offers the potential for very compact primepower systems.

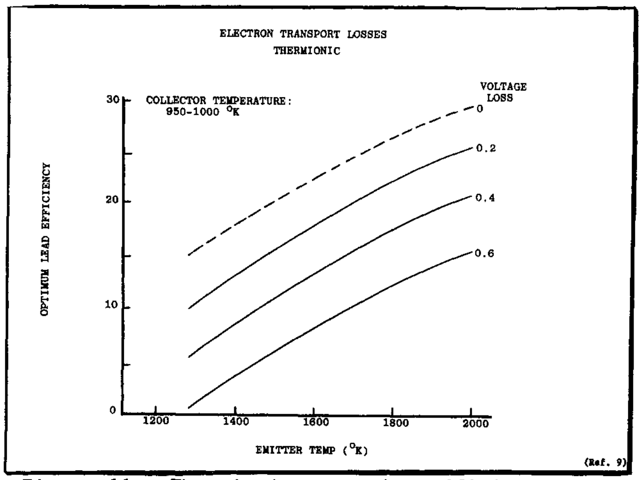

Figure 11. Thermionic coversion efficiency vs temperature of emitter for various interelectrode voltage drops.

Several research problems in thermionics must be addressed: high temperature operation requires understanding and control of materials at elevated temperatures, both within the converter itself and in the heat rejection system that can, in principle, operate with relatively high temperature waste heat. The details of particle density and temperature distributions within the converter are a separate area of concern, since the efficiency of thermionic converter operation depends critically on the self-consistent potential distribution from cathode to anode. Improvements by altering electrode geometries, ionization/ neutralization, etc. are predicted theoretically and can be examined. The particular details of thermionic converter design are subject to applications (e.g., in-pile operation is concerned with neutron effects). The ability to analyze, perdict, and verify interactions of plasmas with electrodes and insulators, particle density and temperature distributions in alkali-metal discharges,

etc. are a basic research goal appropriate to thermionic converters, MHD generators, and various electric propulsion schemes.

Overcoming the electron space charge limit on current density without increasing the interelectrode voltage drop remains a key efficiency obstacle. As seen in Figure 11, lead efficiency is reduced two percentage points for each 0.1 volt drop across the interelectrode space.[9] An attempt to close the electrode spacing places even more stringent demands on the materials' high-temperature performance.

Materials

The eariler sections have repeatedly noted the importance of obtaining data and understanding of materials at high temperatures, the behavior of interfaces between solids, liquids, gases, and plasmas, and the interactions of photons with matter. Facilities for obtaining data at elevated temperatures ($>$2000 °K), for controlling sample purity, especially at surfaces, and for evaluating longterm behavior of materials (e.g., creep, loss of fatigue stress) are far from trivial and are not generally available. An important area of concern is, therefore, the development of the means for conducting basic research, using either existing facilities created in response to particular device requirement, or new user-oriented facilities.

Material modification techniques can be attempted, but considerable care must be taken to prepare and characterize samples. Progress has been made in such areas as ion bombardment to improve the film coefficient for heat transfer at surfaces, ion beam generation of diamondlike coating, and deep impurity trapping to create new semiconductors. The number of possibilities and combinations is great. Improved theoretical/ calculational tools will be necessary to evaluate data and to guide the selection of materials and techniques. Experimental techniques, with calculational support, will be needed that have considerable flexibility to characterize a variety of new materials and arrangements.

Purdy[10] recently listed selected materials activities which should be undertaken to meet future space challenges from a systems and structures, as well as power, perspective. The suggested research areas, in addition to high-temperature radiator and electronic materials include: low outgassing materials, external surface coatings, ultrahigh stiffness materials, dimensionally stable materials, and materials with internal damping.

Heat

The final functional category in a space prime-power systems is the rejection of waste heat. For intermittent use of short duration, waste heat can be stored in matter that is either ejected or retained and cooled subsequently by other techniques at lower power. Steady state operation in space requires heat rejection by radiation. For the temperature ranges of interest and the materials available, such radiation follows a blackbody-like behavior and is thus a strong function of temperature ($\propto T^4$). Much of the effort in achieving high levels of heat rejection capability have been concerned with techniques for heat transport from converters to radiator panels.

A major component of such transport is generally the heat pipe, in which a self-pumping flow cycle is established by vapor-flow, condensation, and capillary return of liquid coolant. Although the operation of heat pipes has been demonstrated successfully, their use in complicated geometries (e.g., sharp turns) and improvement in specific power flux, reliability, etc. require greater understanding in areas such as surface wetting, capillary flow, two-phase flow stability, condensation, etc. The effects of surface preparation, coatings, geometries, material compatibility at high temperature, etc. need to be evaluated. Basic research is needed on two-component flows and interactions of liquids and condensing vapors with surfaces. Such research could be applicable to two-phase flows in heat transfer systems, in thermodynamic cycles (dynamic conversion systems), liquid-metal MHD generators and liquid-radiator schemes.

The use of liquid-films or -droplets to create a large, low-mass surface for heat radiation has been proposed for high-power space systems. The particular schemes have problem areas that would need to be addressed in exploratory development. More general topics, however, for basic research interest include the interactions of liquids with space-plasmas (individually and in clouds or streams) and heat transfer, wetting, stability, etc. of liquid streams and droplets interacting with surfaces, emissivity of liquids in the IR, vacuum charging effects, collection at zero g, and transmissivity in the visible region, among others.

Systems

The interactions of large structures (solid or liquid) with spaceplasmas, fields, and radiation should be examined on a general basis to provide guidance for design and evaluation of particular systems, (e.g., radiators, solar collectors, antennas, shields, mirrors, etc.). Such interactions include both shortterm events (surge currents, voltages in storms) and longterm degradation (e.g., electrocorrosion, drag, etc.). Basic material data are also needed for the design of large space structures (thermal, electrical, mechanical characterization of construction materials and predictions for new materials).

Summary

The preceeding section provides a rapid survey of space prime-power technology and the research problems associated with particular functional or technical categories. Although there are many particular research topics that require attention, three areas of basic research are indicated that would support future development of prime-power for high energy space systems:

1. Characterization and Design of Materials
2. Fluid Interactions
3. Plasma Interations

Within these three areas are distinct, but related topics. The last two areas will couple to the first area for those interactions that depend upon material properties at surfaces. Delineation of the three areas above can be associated with the technical specialties that may be required for successful research in these areas: solid-state physics, fluid mechanics, and plasma physics, respectively.

Two additional items should be mentioned, however: diagnostics and facilities. The ability to perform facilities. The ability to perform successful research in the parameter space of interest in any of the three areas mentioned above will require much effort in diagnostic design and instrumentation, and in the construction of suitable test facilities. Without parallel improvements in fast diagnostics, high-temperature techniques, etc., the breakthroughs

demanded by high-power systems will not be forthcoming.

Characterization and Design of Materials

There are two extremes of approach and need in this research area. The basic physical chemical laws governing the structure of matter can be examined, extended, and utilized to devise new materials and combinations of materials that have desired properties to advance space prime-power. Material modification techniques (e.g., ion bombardment, impurity trapping) can be developed, guided by theoretical and experimental tools. Eventual applications will be to improved solar cells (e.g., tandem), lower corrosion, new catalysts, high-temperature dielectrics, etc.

A more mundane avenue of endeavor is the characterization of material properties, especially at high temperatures (2000 °K). Experimental facilities and techniques are required for life-testing structural materials, measuring creep stress characteristics, loss of fatigue strength, etc. Characterization of structural properties is also needed for new materials at lower temperatures (for larger spacestructures, high-pressure fuel cells, etc.)

Fluid Interactions

Flow of liquids and gases through various structures and under various conditions of temperature and pressure is found in many space prime-power concepts. Very often the flow interacts with boundaries resulting in corrosion or wear. Boundaries guide and support desirable flow behavior as well (e.g., capillary flow in heat pipes). Factors affecting the interactions of liquids and solids need to be examined, e.g., the influence of surface preparation on wetting and heat transfer. Interaction of flows with suspended liquid or solid droplets is a concern in several heat transfer schemes. Characterization of fluid material properties at high temperature is also necessary (e.g., potassium, tin) in order to predict behavior for dynamic conversion, heat transport, heat rejection, etc. Chemical effects on boundaries (corrosion, fuel-cell operation, etc.) can be examined in conjunction with surface modification techniques.

Plasma Interactions

Plasmas occur in space prime-power systems both internally (thermionic diodes, MHD generators) and externally (space-plasma surrounding radiators or collectors). The distributions of particle density and temperature within power converters are critical to performance. Such converters include not only the standard thermionic and MHD techniques but also new concepts (e.g., photon conversion to electricity in solid or gaseous plasmas). The interactions of plasmas with electrodes and insulators (particle bombardment, chemical reaction, erosion) are important to system lifetime. Non-equilibrium conditions associated with MHD boundaries, critical ionization and recombination rates, insulator degradation processes, and the behavior of plasmas in turbulent flow are representative research issues.

High-energy plasma particle bombardment of insulators, liquidfilms, droplets, etc. can cause long-term degradation of power systems. Short-term electrical surges supported by space-plasmas can damage large structures associated with high power space systems. Theoretical and experimental examination of plasma interactions in the context of space prime-power systems can guide the development of improved converters, and also avoid otherwise unforeseen difficulties with large spacesystems operation.

References

1. M. E. Cohen and M. Weinter, "Space Power Technology for the Military Space Systems Technology Model." The Aerospace Corporation, El Segundo, CA (a Report ToR-0082 (2909-63)-1, 1982.

2. J. P. Mullin, "Space Energy Conversion," A review for the G.E. Space Technology Seminar, Valley Forge, PA, Feb 83.

3. M. S. El-Genk & D.M. Woodall, "Areas for Research Emphasis in Design of the Space Power Advanced Reactor" Proceedings of the AFOSR Special Conference on Prime Power for High-Energy Space Systems, Norfolk, VA, Feb 22-25, 1982.

4. J. Preston Layton, "Power Conversion: Overview", Proceedings of the AFOSR Special Conference on Prime Power for High-Energy Space Systems, Norfolk, VA, Feb 22-25, 1982.

5. J. B. Dicks, "MHD Power: Overview", Proceedings of the AFOSR Special Conference on Prime Power for High-Energy Space Systems, Norfolk, VA, Feb 22-25, 1982.

6. N. T. Saunders, "Overview of High Temperature Materials for High Energy Space Power Systems" Proceedings of the AFOSR Special Conference on Prime Power for High-Energy Space Systems, Norfolk, VA, Feb 22-25,1982.

7. Space Systems Technology Model, NASA, Office of Aeronautics and Space Technology, Washington, DC, Sep 81.

8. R. M. Hord, private communication.

9. L. Yang and G. Fitzpatrick "Therminonic Conversion for Space Power Applications, Proceedings of the AFOSR Special Conference on Prime Power for High-Energy Space Systems, Norfolk, VA, Feb 22-25, 1982.

10. D. M. Purdy, "Evaluation of New Materials for Space Applications", 24th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Materials Conference, Lake Tahoe, Nevada, May 2-4, 1983.

11. R. Smith, DOE (Germantown), Private Communication.